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14. ABSTRACT <p>The scattering properties of the medium ultimately determine the outcome of the image transmission. For ocean optics research, the scattering properties are often conveniently described and measured in general by the scattering coefficient (b), which determines the possibility of a photon to be scattered away from its original traveling direction per unit length by the medium molecules, constituents within (i.e. particles [1]), and turbulence [2]. As we know, this parameter (b) is an integration of the volume scattering or phase function, B, which details such probability by the relative directions of incoming and out-going photons [1]. These inherent optical properties (IOP), although measured frequently due to their important applications in ocean optics, especially in remote sensing, cannot be applied to underwater imaging issues directly, since they inherently reflect the chance of the single scattering.</p>					
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Current Problems in Optics of Natural Waters

An aerial photograph of Nizhny Novgorod, Russia, showing the city's architecture and its location on the banks of the Volga River. The image is in black and white and has a grainy, textured appearance. In the foreground, there are dense trees. In the middle ground, a large, multi-story building with a distinctive pyramid-shaped roof is visible. In the background, the city extends along the riverbank, with various buildings and structures. The text 'ONW'2007' is overlaid on the lower part of the image.

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A PRACTICAL POINT SPREAD MODEL FOR OCEAN WATERS

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1. Background

The scattering properties of the medium ultimately determine the outcome of the image transmission. For ocean optics research, the scattering properties are often conveniently described and measured in general by the scattering coefficient (b), which determines the possibility of a photon to be scattered away from its original traveling direction per unit length by the medium molecules, constituents within (i.e. particles [1]), and turbulence [2]. As we know, this parameter (b) is an integration of the volume scattering or phase function, β , which details such probability by the relative directions of incoming and out-going photons [1]. These inherent optical properties (IOP), although measured frequently due to their important applications in ocean optics, especially in remote sensing, cannot be applied to underwater imaging issues directly, since they inherently reflect the chance of the single scattering.

The point spread function (PSF) describes the system response to a point source in the medium, which includes the effect of multiple scattering. It is the ideal parameter to study image transmission, optical sounding [3], reversion of transmission effects, and retrieval of optical properties [4]. Generally speaking, a 2-dimensional image of an object is the combination of original signal, $f(x,y)$, convolved by the imaging system response of a point source, the point spread function or PSF $h(x,y)$, integrated over sensor space Ξ :

$$g(x, y) = \iint_{\Xi} f(x_i, y_i) h(x - x_i, y - y_i) dx_i dy_i. \quad (1)$$

The system response includes those from both the imaging system itself, as well as the effects of the medium (water in our case). With known characteristics of the imaging system and correct modeling of the medium, theoretically it is possible to recover the original signal by reversion or deconvolution [4, 5]. Mathematically PSF is equivalent to the beam spread function (BSF) [6] which can be easier modeled and measured.

Duntley [7] reported extensive lab measurements of BSFs of simulated ocean waters with remarkably different optical lengths (0.5 to 21), and summarized their findings in a single, albeit complex empirical relationship:

$$PSF(\theta) = \frac{10^{A-C} \theta^B}{2\pi \sin \theta} \quad (2)$$

with parameters $A = 1.260 - 0.375\tau^{0.710+0.489/\zeta} - (1.378 + 0.053\zeta)10^{-(0.268+0.088)\tau}$,

$$C = \frac{1}{3} \left[1 - \left(\frac{\theta^{3/2} + E}{E} \right)^{2/3} \right],$$

$$E = (13.75 - 0.501\zeta) - (0.626 - 0.357\zeta)\tau + (0.01258 + 0.00354\zeta)\tau^2,$$

$$D = (0.018 + 0.011\zeta + 0.001725\tau)\tau \text{ and } B = 1 - 2(10^{-D}).$$

Notice in above equations the optical length defined as $\tau = cr$ (c being the total attenuation coefficient), while the single scattering albedo is $\omega_0 = b/c$. $\zeta = 1/(1 - \omega_0)$ is used to simplify the form.

Another empirical effort was carried out by Voss [8], fitting field measured data from 3 different types of oceanic waters (TOTO, Pacific and Sargasso Sea) to the following form:

$$PSF(\theta) = B_1 \theta^{-m}, \quad (3)$$

where B_1 is a constant and $-m$ is the slope of $\log(PSF)$ vs $\log(\theta)$. While m is not a constant, but rather a function of IOP and τ , the above formula can fit all data to less than 15% error. The m values ranged from 0.4 to 2.0 as a function of τ (0 to 10). Other than graphical results, there is no definitive relationship provided to allow comparison of this method to other approaches. Nonetheless, this is encouraging.

ing result, since such simple relationship can be rather beneficial to imaging needs, especially when high frame rate, per pixel calculations are desired and hardware implementation is needed. The aim of paper is to examine the relationship of the PSF to commonly measured IOPs in search of a simpler solution for real-time imaging needs, rather than thoroughly review PSF models (such as some of the more sophisticated analytical models [9–11]), although comparisons will be made amongst measured PSFs to validate our results.

2. Theory

The above mentioned empirical results, while useful, lacks the benefit of physical interpretations of each parameters involved. Analytical solutions, while at times complex or approximated, offer clear answers to physics involved and help to check numerical solutions.

Without including all the details here, Wells [12] demonstrated that under small angle scattering approximation (SAA), and a phase function in the following form:

$$\beta(\theta) = \frac{b\theta_0}{2\pi(\theta_0^2 + \theta^2)^{3/2}}, \quad (4)$$

the modulation transfer function (MTF) can be expressed in a closed-form as

$$H_{medium}(\psi, r) = e^{-D(\psi)r}, \quad (5)$$

$$D(\psi) = c - \frac{b(1 - e^{-2\pi\theta_0\psi})}{2\pi\theta_0\psi}, \quad (6)$$

where θ_0 is related to the mean square angle (MSA). The PSF can be calculated numerically using above relationships via inverse Fourier transform, or analytically can be expressed in 1st order terms as those formulated by Alan Gordon [12]

$$PSF(\theta, r) = \frac{d\Phi}{d\omega}, \quad (7)$$

$$\Phi(\theta, r) = \exp\left[-\left(c - \int_0^1 \int_0^{\theta/t} \beta d\omega dt\right)r\right], \quad (8)$$

$$PSF(\theta) = e^{-\tau} r \int_0^1 \beta\left(\frac{\theta}{t}\right) \frac{dt}{t^2}. \quad (9)$$

From (4) and (9), we approximate the integration with the following form:

$$PSF(\theta) = K \frac{bre^{-\tau}}{2\pi\theta^n} = K \frac{\omega_0 \tau e^{-\tau}}{2\pi\theta^n}, \quad (10)$$

where K is a constant and does not affect imaging needs since relative units of PSF are used. By comparing to simple numerical calculations using Fourier transformed MTF, we found that $n = 1/\omega_0 - \tau\theta_0$ gives the best result over different parameter ranges. We will further compare these with empirical and measured results.

3. Results

Data were obtained during an April-May 2006 NATO trial experiment in Panama City, Florida. The amount of scattering and absorption were controlled by introducing Maalox and absorption dye respectively into a tap-water filled pool. In-water optical properties during the experiment were measured. These included the absorption and attenuation coefficients (Wetlabs ac-9), particle size distributions (Sequoia Scientific LISST-100), and volume scattering functions (multi-spectral volume scattering meter or MVSM).

The measured volume scattering functions are used in Monte Carlo (MC) simulations to derive the PSFs, that are used in comparison to other approaches. The main computer code uses MC to calculate the PSF using only the inherent optical properties. This method is essentially a numerical experiment of the physical process under consideration, and is based entirely on first principle calculations

which divorce it from any other assumptions or theories. The disadvantage of this generality is the long computer time required, since the results are statistical in nature and each set of parameters must be run separately. The MC method has in fact been used previously to test the range dependence of the Wells theory [13]. Now rather than calculate the PSF directly, the mathematically equivalent but computationally simpler beam spread function (BSF) is calculated instead. The BSF is defined as the normalized irradiance distribution on a spherical surface of radius R centered on a unidirectional transmitter, and this definition provides a prescription for the Monte Carlo method to follow. Given the IOPs (phase function, absorption and scattering coefficients), the radius of the sphere R , and an angular resolution $\Delta\theta$, the code produces the irradiance for each angular bin over the entire sphere.

Comparison of PSFs from different methods mentioned (i.e., *current* study, MC simulated PSF from measured *MVSM* phase functions, and *Duntley's*) are shown in Figs. 1, 2, and parameters listed in Table 1.

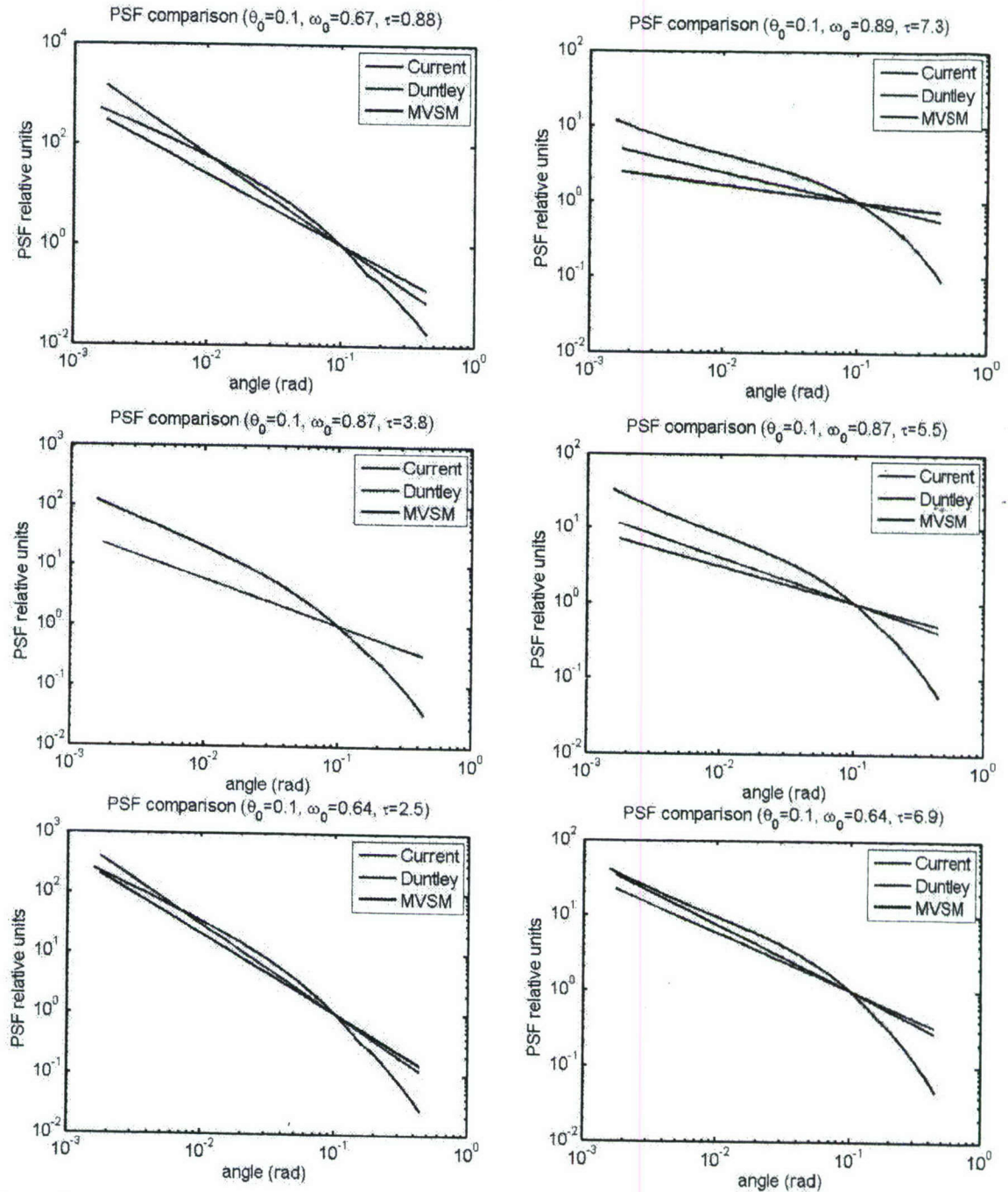


Fig. 1. Comparison of PSFs from different methods: “This” (current study), “Duntley” (empirical relationship in text), and “MVSM” (Monte Carlo simulated PSF based on measured volume scattering function) during NATO experiment. Normalized to 100 mrad. See text for details.

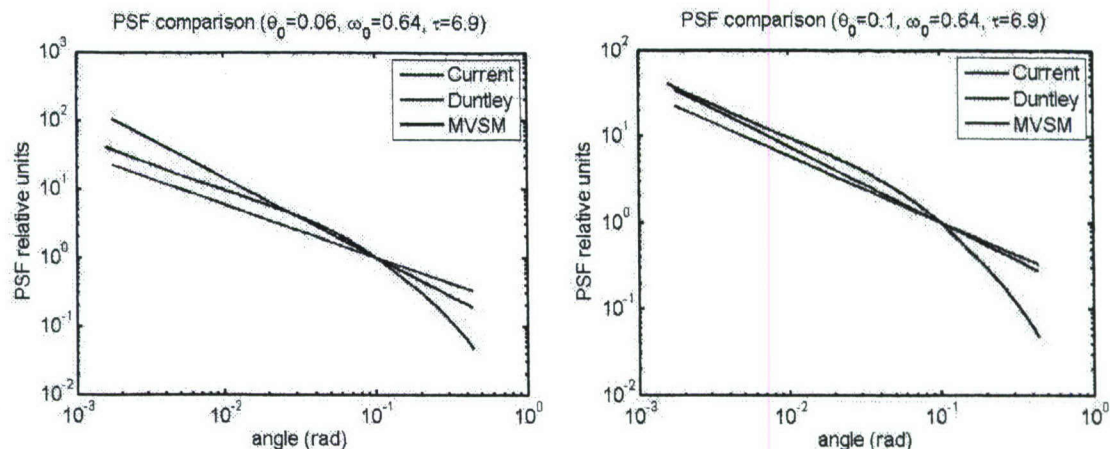


Fig. 2. An example of PSF comparison under different θ_0 values. Notice that a higher value of the mean square angle value seems to work better. This is true for other situations (not shown) as well. Normalized to 100 mrad.

Table 1. Optical parameters used to compare different PSF models as shown in Figs. 1–2

Date	optical length (τ)	measured c (m^{-1})	scattering albedo (ω_0)
4/27/2007	3.8	0.78	0.87
4/27/2007	5.5	0.78	0.87
4/30/2007	0.88	0.22	0.67
5/01/2007	7.3	1.38	0.89
5/2/2007	2.5	0.91	0.64
5/2/2007	5.5	0.91	0.64

The current approach matches well with both measurements under different testing conditions shown, and can be considered an able substitute for imaging processing purposes [13]. One may notice from Figs. 1, 2 differences can be observed between the two measured results, and that of MVSM is always higher than Duntley's. This is likely due to the difference in scattering agents involved, as the particle sizes will be different by the different preparation process (recall that Duntley used high purity filtered water as their experiment base in the tank, before adding similar absorption and scattering agents). In fact, the differences in PSF can be as high as an order of magnitude under certain conditions at small angles (eg. $\omega_0 = 0.87$, $\tau = 5.5$), or ± 1 in PSF log slope. Examination of the parameter related to θ_0 suggest that a higher value (0.1) is more appropriate for the data involved (Fig. 2). Initial testing with imagery obtained during NATO experiment show little differences using any of the PSFs under typical conditions tested [4, 14]. It is worth pointing out, however, that the current approach matches those from Duntley's well to at least $\tau = 15$.

4. Summary

A semi-analytical point spread function that is related to Wells/Gordon's formulation is presented and show close fit to two independent measurement results under different conditions. Monte Carlo simulated PSFs are calculated, using MVSM-measured phase functions. Both results tested well against previous empirical results from Duntley at various optical lengths and scattering contributions. The fact that different scattering agents can result to an order of magnitude difference in PSFs between measured MC-MVSM and Duntley's at small angles, or in other words, affecting the slope of the PSF significantly, suggest additional studies are needed, particularly in natural oceanic waters.

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